Final Report (Phase I)

Optimal Linkages for Coal based power generation in India

Collaborative Project of TERI & the University of Kyoto

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Executive Summary

This report describes the work that has been carried out by TERI and the University of Kyoto over the first year of the Collaborative Project on Optimal coal supply linkages for coal based power generation in India.

The overall aim of the project was to set up a simple modeling framework to examine optimal coal supply linkages for coal based power generation in India.

The literature review on the subject revealed that though there are a number of issues that are often talked about in the coal and power sectors, a comprehensive micro level model of this nature has not been set up to examine various linkages in the sector in India. The collaboration between TERI and the University of Kyoto is timely at this juncture and is expected to be extremely relevant in terms of providing an in-depth understanding of the problems that ail this sector at every stage in the process.

Towards this end a model framework has been set up which is subsequently discussed in this report. The data that has been compiled so far is also discussed briefly in the following sections. The scenario runs are however not discussed at this stage since the data available so far is not detailed enough to be able to provide rational model simulations. Efforts towards procuring better quality data are underway and, it is expected that more detailed data would be available in due course of time. Further refining of the model structure along with data compilation would be continued in the second phase of the Collaborative project and the discussion on scenarios would be available in the subsequent report submitted to the JST on completion of Phase 2 of the project.

In keeping with the objectives of the CREST project, Phase 2 would also ensure that the project scenarios indicate some possible directions with regard to the kind of collaborative activity that can be taken up between Japan and India for the future.

The major limitation faced during the first phase of this study was related with the poor documentation and unavailability of detailed data in the sector. Though most of the data is compiled by Coal India Limited (CIL), Central Electricity Authority (CEA), the Indian Railways and the individual power plants, this is often not easily available. On the other hand, the use of aggregate data leads to a situation whereby the model is not able to make a unique optimal choice. In this light, it is important to gather, compile and input reliable and disaggregate data to the model, in order that the results and analysis are meaningful.

This report has 7 sections. Section 1 describes the problems in coal based thermal generation in India and lays the background under which this study has been undertaken. Section 2 examines the current situation of coal utilization for power generation in India. Section 3 describes the target of model development. Section 4 describes the structure and data of the model. Section 5 provides the equation listing of the model in the current form. Section 6 discusses the possible scenarios that would be analyzed through the model. Section 7 lists out the future plan of work for model extension and further analysis of issues.

Section 1 Introduction

1.1 Problems in Coal based thermal generation in India

Electric power is one of the most vital infrastructural inputs for the socio-economic development of any country. The trends of liberalization and globalization have led to increased industrial and commercial activity and therefore high growth of power demand. The demand for electric power is rapidly increasing at about 8% compounded growth rate. Increased power demand has outpaced all plans for capacity additions that were envisaged and India is faced with both energy and peak shortages. According to TERI estimates, by 2011/12, the requirement for power generation would increase to 1200 billion kWh from a level of 400 billion kWh in 1997. It is also expected that coal would continue to be the major indigenous source of energy in the mid-term to fulfill the country's energy needs, even after allowance has been made for conservation programmes, development of solar and other renewable sources, and, some substitution from increased use of oil and gas. Planning for the efficient and economic use of coal is therefore extremely significant at this juncture.

Of the total estimated coal reserves of 194 billion tonnes in India, 85% is of non-coking coal variety and only 15% is of coking variety. Further, 33% of the reserves fall under the "proved" category, 44% in the "indicated" category and 23% in the "inferred" category.[1]

The country's coal occurrences are distributed along the river valleys - Damodar Valley, Son-Mahanadi valley, Pench-Kanhan valley, Wardha-Godavari valley. There are 44 major coalfields in the peninsular India and another 17 located in the northeastern region. The bulk of the coal reserves are confined to the southeastern quadrant of the country in West Bengal, Bihar, Orissa and Eastern Madhya Pradesh as shown in the map below. The main coal deposits in India are located in a triangle, of which the western edge is the center of the country and the eastern corner is 150 kilometers west of Calcutta. The oldest coalfields of Raniganj and Jharia are in the East, producing the best quality metallurgical and non-metallurgical coals covering half of the country's total production. The trend in the past decade has been towards more development in the Western part of the triangle of the coal belt in India.

Coal in India needs to be transported by rail network over distances as far as 500-1500 km and therefore the cost of transportation is often more than the pithead price of coal. Transporting coal within a large country like India is a major issue and India with the third largest rail network in the world obviously depends largely on rail transport. Moreover, given the huge quantum of coal that is needed for power generation, road movement is more or less ruled out for this purpose. Coal movement for power generation is therefore mostly by rail with a small amount being transported by MGR. The linkages for coal movement are regularly fixed for the movement of coal from mines to power plants. Whether these linkages are optimal or not (such that the choices are based largely on economic criteria) should be carefully examined given that the issue of coal transportation is fairly important.

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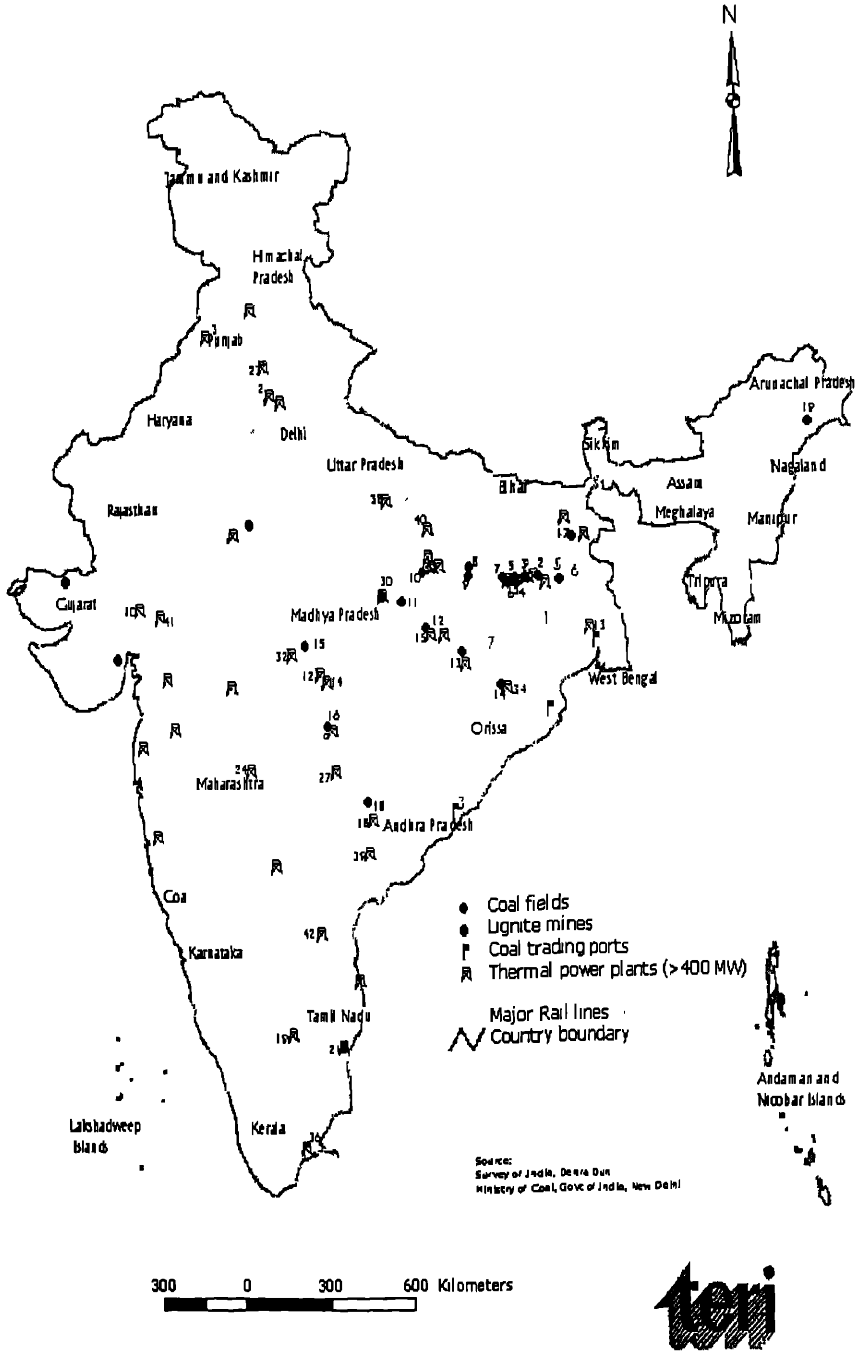
[1] Coal Atlas of India, Coal India Limited, 1993.



teri

Coal Fields

1	Ranigunj	6	South Karanpura	11	Sohagpur	16	Wardha valley
2	Jharia	7	North Karanpura	12	Korba	17	Rajmahal
3	East Bokaro	8	Daltonganj	13	Ib river	18	Gadavari
4	West Bokaro	9	Hutar	14	Talcher	19	Makum, Namchik-Namphuk
5	Ramgarh	10	Singrauli	15	Pench-Kanhan		

The second issue is with regard to the quality of Indian coals. The quality of Indian coal is in general inferior with a high ash content. Coal used for power generation often has an ash content of between 35-45%. Another feature that is specific to Indian coal is that the insignificant difference in specific gravity between coal and dirt makes it difficult to wash the coal. This implies that huge amounts of dirt move with the coal being transported to the power plants placing a stress on the capacity of the rail network as well as increasing transportation costs. The Ministry of Environment and Forests has issued a notification in its gazette that all coal being used in power plants with a capacity of greater than 1000 MW should use washed coal with an ash content of no more than 34%. The nature and extent of benefits that could ensue from washed coal are therefore sought to be examined through scenario comparisons in this study.

The third issue deals with the efficiency of power generation technology itself. About 64% of India's installed power generating capacity is coal fired. It is therefore necessary to examine whether these plants operate in an efficient and clean manner such that there is optimal coal utilization. This is especially relevant at the end-use point from the environmental point of view and the emissions that are released from power generation.

1.1 Purpose of the work

Given that the coal based power sectors is plagued with a number of problems such those discussed above, it was proposed to target an in-depth examination of the nature and magnitude of these problems. For this purpose, it was felt that a linear programming model would serve as the best tool to compare the existing and likely scenario against the alternative scenarios. The benefits from one or more of the alternative scenarios would be assessed through the model so as to provide directions towards which the sector ought to move in terms of policy changes and also to help identify areas for possible collaboration with Japan.

Section 2 Current situation of coal utilization for power generation in India

About 64% of India's installed power generating capacity is coal fired. As per the recent notification of the Ministry of Environment and Forests, coal moved to new plants of over 1000 MW capacity would have to be washed to levels of less than 34% ash content. This implies that either there should be more pithead generation or coal should be washed unless imports of coal are to be resorted to. Already, the government has sanctioned two non-coking coal, washeries with a total capacity of 14.5 million tonnes/ annum (Piprawar 6.5 mt/a, Kalinga 8 mt/a). The Piprawar washeries has been commissioned in 1998. Also, some capacity has now been approved to be taken up for coal washing in the private sector.

The availability and PLFs of thermal power projects in India are reletively low and of a substancial scope for improvement. The availability of thermal power generating unit in the developed countries is significantly higher than what may be considered as normative in India. This is largely due to factors such as poor quality of coal, lack of coal processing facilities, inadequate or insufficient control equipment, aging of many power stations etc. It is felt that there is considerable potential to improve the performance of thermal power stations.

Section 3 Target of model development

Given the complexity of problems that exist in the coal based power generation sector, it was clear that the entire process from the point of coal supply to transportation, coal washing, and utilization at the power plant needed to be examined. Since no similar study has been attempted earlier, a replication of the existing or "reality" scenario was proposed to serve as a base for scenario comparisons. This "reality" situation can then be compared with the "most optimal" situation and other scenarios in order to appreciate the magnitude and nature of problems at each stage of the processes.

It was decided that the development of a static linear programming model for such an exercise would be most useful as the "optimal" solution can be obtained in terms of the most economically efficient combination of supply-demand linkages provided to the model across various scenarios.

Moreover, given that India has more than 20 coalfields and about 50 thermal plants connected with a huge railway network traversing the length and breadth of the country, an examination of any shifts from the "reality" scenario would be a near impossibility without the help of a modeling tool such as that developed in this study.

The model thus developed is expected to be able to provide a quantification of the magnitudes of deviations from the optimal situation at various stages. However, it must be remembered that there are a number of qualitative issues that cannot be captured in a strict modeling framework and the model should be used only to look at directions for change. A qualitative assessment would need to be coupled with the model results in order to arrive at ant rational suggestions for the sector. Using the above methodology, the overall study is expected to provide policy insights into the sector and provide an idea of costs that must be borne if we must move towards more environmentally benign scenarios.

The environmental study is restricted quantitatively to the emissions emanating during power generation. Water pollution due to the discharge of slurry from the washeries is not included in the scope of the study and may be qualitatively discussed.

Section 4

4.1 Brief Review of Activities in Phase -I

Literature review

As a first step a thorough literature review of published information sources for coal and power related data was undertaken.

Methodology formulation

As discussed in Section 3 of this report, the need for a modeling framework was felt in order to examine the linkages existing in the coal based power generation sector in

India. For this purpose, various softwares such as GAMS or UNIX could be adopted. However, since facilities for working on UNIX platforms were not available at TERI, the GAMS software was chosen for this exercise. Modeling with GAMS was also a new expertise that was required to be picked up and this was done during the visit of TERI professional to the University of Kyoto in April, 1998. Apart from learning the GAMS language, it was also required to learn in detail the technical processes at various stages of the sector in order to formulate the equations for the model. Where detailed process characteristics were not available, as in case of the washery process, regression equations were fitted on existing data to obtain proxy parametrs for process design. The detailed model as currently described in section 5 is however still subject to revision.

Procurement, classification and compilation of data
Various departments and agencies of the Indian Government are responsible for compiling data on coalfields, coal movement and power gencration. However, the data is often not in a readily available form and needs to be compiled and brought into a usable form.

The Ministry of Coal documents information regarding the gradewise production of coal from each colliery. The collieries are generally listed by their ownership (by Company), but for purposes of the model it was necessary to identify each mine by the coalfield that it belonged to. This classification was accomplished with the help discussions with coalfield experts at TERI

The list of thermal power plants in India was compiled from documents of the Central Electricity Authority. Data on installed capacities and efficiencies of plants have been classified by plant, but unit-wise data if available would be used in the next phase to account for differences in efficiencies among units within a plant.

The Railway networks for transportation of coal between each of the coalfields and power plants identified have been compiled in a matrix and transportation distance as well as tariff data for such movement has been input for the base year.

4.2 Outline of model framework

The structure of the COLINK model in terms of the basic building blocks is schematically represented in Figure 1.

The model is driven by a set of exogenously provided regional demands for coal based power generation in the country. This demand is provided across 5 regions of the country, viz. North, South, East, West and North-East. Choices for using power generation technology (reflected by technological and availability characteristics of plants within a region), alternative rail routes and choice of coalfields with various grades of coal are provided as options to the model. Based on the exogenously determined demand level, the optimal scenario in the unconstrained model would determine the best mix of possible options. Regional demands may be met from one or more plants located in the region depending on the power requirement, the capacities, efficiencies and costs of power generation at each of the plants. The choice of plant capacities leads to the requirement of coal at each plant depending on the heat rate of the plant and the quality of coal. Further, the gradewise coal drawn from one or more coal fields for each plant moves through a rail network depending on available linkages and cost parameters. Capacity bounds on gradewise availability of coal at each coalfield place restriction on the amount of coal that can be picked up from any source. Washeries may or may not be chosen in a model solution depending on the requirement for coal quality (led by environmental scenarios). Emissions are calculated in the model based on given emission ratios. The objective function represents the total costs to the economy and the resultant emissions are provided as an output based on environmental factors built into the processes and control technologies.

The emissions as well as costs under the optimal case can then be compared with a most likely scenario depending on existing links to examine the level of variation. The resultant variation would then be qualitatively assessed to understand why the optimal linkages are not being utilized. Alternative policy scenarios are also proposed to be examined to compare the impacts on costs and emissions under scenarios of increased plant efficiencies, increased capacity for coal washing, better end-of-pipe emission control technologies etc.

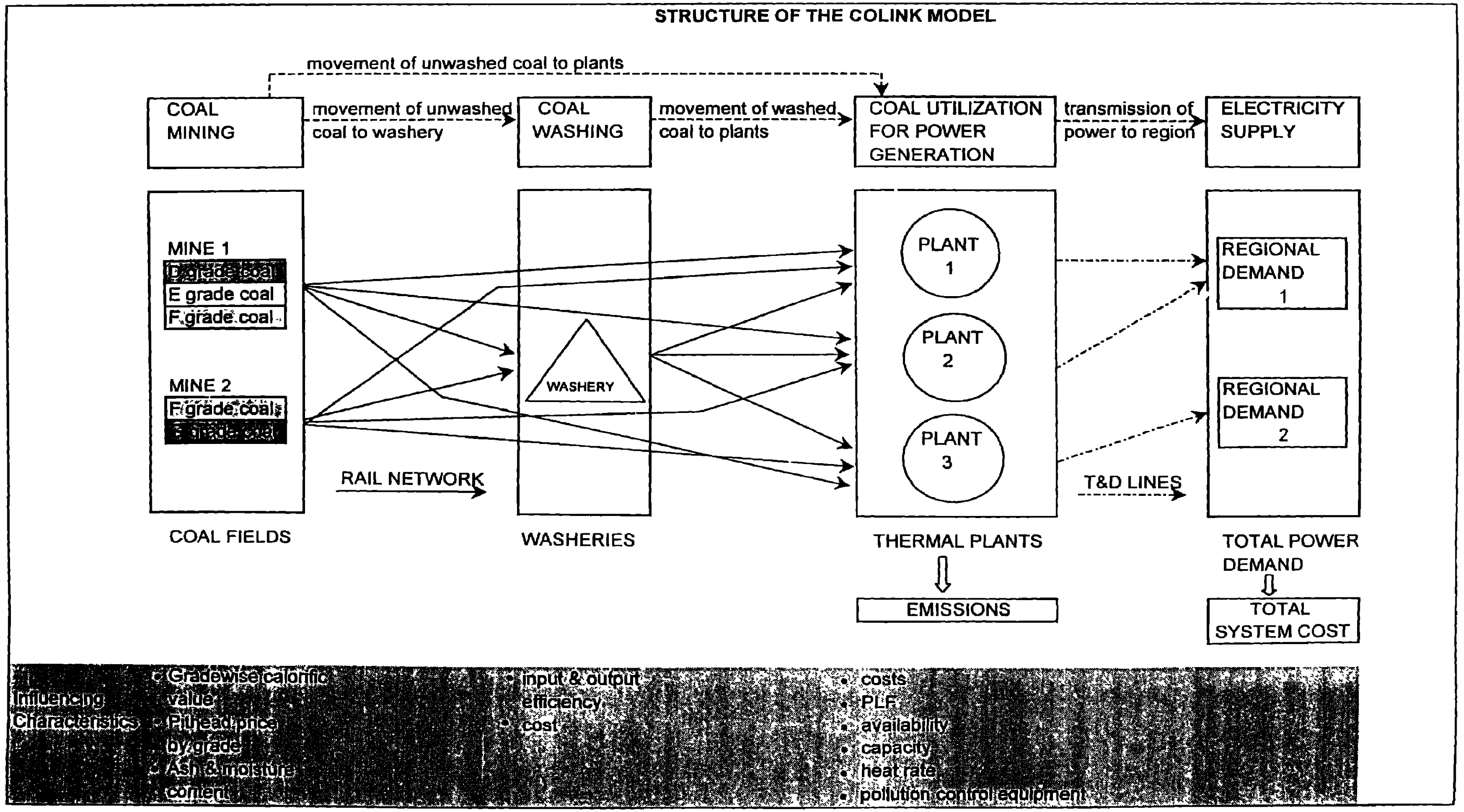

STRUCTURE OF THE COLINK MODEL
movement of unwashed coal to plants
COAL MINING
movement of unwashed coal to washery
COAL WASHING
movement of washed coal to plants
COAL UTILIZATION FOR POWER GENERATION
transmission of power to region
ELECTRICITY SUPPLY
MINE 1
D grade coal
E grade coal
F grade coal
MINE 2
F grade coal
G grade coal
RAIL NETWORK
WASHERY
PLANT 1
PLANT 2
PLANT 3
REGIONAL DEMAND 1
REGIONAL DEMAND 2
T&D LINES
COAL FIELDS
WASHERIES
THERMAL PLANTS
EMISSIONS
TOTAL POWER DEMAND
TOTAL SYSTEM COST
Influencing Characteristics
• Gradewise calorific value
• Pithead price by grade
• Ash & moisture content
• input & output efficiency
• cost
• costs
• PLF
• availability
• capacity
• heat rate
• pollution control equipment

Figure 1.

Section 5: Detailed model structure

```
* Model name COLINK dated April 99 Author Ritu Mathur, TERI
□

□

$if exist intro.gms
□
$include intro.gms
□

□
* ******************************************************
*       The intro.gms file will call a program that    *
*       would explain what the colink model does       *
* ******************************************************


*         ----------------
*             SETS
*         ----------------
Sets
$if exist coalfld.gms
$include coalfld.gms

* ******************************************************
*       Coalfld.gms is called into the source code     *
*       to include all the coalfields in India         *
*       3 alphanumeric characters define a field       *
* ******************************************************

$if exist plants.gms
$include plants.gms

* ******************************************************
*       plants.gms is called into the source code      *
*       to include all the thermal plants in India     *
*       4 alphanumeric characters define a plant       *
* ******************************************************

$if exist NRplants.gms
$include NRplants.gms

$if exist ERplants.gms
$include ERplants.gms

$if exist SRplants.gms
$include SRplants.gms

$if exist WRplants.gms
$include WRplants.gms

$if exist NEplants.gms
$include NEplants.gms

* ******************************************************
*       NRplants,ERplants, SRplants,WRplants, NEplants *
*       are called into the program to include sets of *
*       plants in the North, East, South, West & North *
```

```
*       East respectively.                               *
*       4 alphanumeric characters define a plant         *
*       Each of the above 5 sets are subsets of the      *
*       set plants (that includes all thermal plants     *
*       in India)                                        *
*       Disaggregation on plants by units is currently *
*       subject to the data availability                 *
* *******************************************************

wn washery node /WW1,WW2/
g all coalgrade /A,C,D,E,F,G,L/
* gcol (g) part of coalgrade /A,C,D,E,F,G,L/
* gcol is a subset of set g

tch size and technology combination of plant /500C,210C,
            150C,120C,100C,060C,040C/
alias (NR,NR1);
alias (ER,ER1);
alias (WR,WR1);
alias (SR,SR1);
alias (NE,NE1);
alias (g,gcol);


*        ---------------
*         PARAMETERS
*        ---------------

Parameters
$if exist capfld.gms
$include capfld.gms

$if exist calval.gms
$include calval.gms

* *******************************************************
*       Calval.gms is called into the source code       *
*       to include the gross calorific value of coal    *
*       at each coalfield. The calorific value is in    *
*       kcal/kg or Mcal/tons                            *
* *******************************************************

$if exist ashper.gms
$include ashper.gms


$if exist moistper.gms
$include moistper.gms

$if exist extrcost.gms
$include extrcost.gms

* *******************************************************
*       Extrcost.gms is called into the source code     *
*       to include the extraction cost of coal from     *
*       each coalfield. This would vary depending on    *
*       the geological conditions & type of mining.     *
*       The extraction cost is in Million Rs/mt. At     *
*       present the model takes it as external given    *
*       value but can be made endogenous if adequate    *
*       information is known on how costs vary.         *
```

```
*****************************************************

wshcfcol(gcol) washery conversion factor for coal to grade D
/EG 0.8
 FG 0.7
 GG 0.6 /

calvalwsh would now be set as a variable rather than as parameter
calvalwsh(wn) calorific value of washed coal in each coalfield in
.cal per kg or Mcal per tons
/WW1 7000
WW2 7000 /

wshprash(gcol) production rate of fly-ash from washery
/E 0.4
 F 0.5
 G 0.6 /

wshprres(wn,gcol) production rate of residue from washery process
/WW1.E 0.2
 WW2.E 0.5
 WW1.F 0.3
 WW2.F 0.4
 WW1.G 0.4
 WW2.G 0.5 /

wshcostinv(wn) annualised investment cost for each washery in Rs per
mt
/WW1 500
 WW2 200 /

wshcostopm(wn) operating cost of each washery type in Rs per mt
/WW1 10
 WW2 5 /

wshutlash(wn) ratio of ash utilized effectively at each washery
/WW1 0.80
 WW2 0.40 /

capwshlo(wn) lower bound on capacity of washery input (mt)
/WW1 0
 WW1 0
 WW2 0
 WW2 0 /

capwshup(wn) upper bound on capacity of washery input (mt)
/WW1 500
 WW2 600 /

$if exist pnutlash.gms
$include pnutlash.gms

$if exist heatrate.gms
$include heatrate.gms

powprbash(gcol) production rate of bottom ash from power plant in mt
per mt
/E 0.80
 F 0.82
 G 0.85 /
```

```
powprfash(g) production rate of fly ash from power plant in mt per mt
/E 0.20
 F 0.18
 G 0.15 /

$if exist pcostinv.gms
$include pcostinv.gms

$if exist pcostopm.gms
$include pcostopm.gms

$if exist plfpowlo.gms
$include plfpowlo.gms

$if exist plfpowup.gms
$include plfpowup.gms


$if exist cappowlo.gms
$include cappowlo.gms

* ******************************************************
*       The parameter cappowup provides the maximum     *
*       capacity of a unit that may be picked up. This *
*       needs to be input for each of the plant units. *
*       The least cost technology is picked up first    *
*       followed by the next marginal technology.       *
* ******************************************************

$if exist cappowup.gms
$include cappowup.gms

$if exist spmfac.gms
$include spmfac.gms

$if exist noxfac.gms
$include noxfac.gms

$if exist soxfac.gms
$include soxfac.gms


Scalar
demandN power demand in the Northern region in gWh
/104250/

demandE power demand in the Eastern region in gWh
/35800/

savbrik savings in Rs per mt from making bricks
/ 10 /

lossfac loss factor in transmission
/ 0.23/

trnsNR   loss factor in transmission in NR
/ 0.22/

trnsER   loss factor in transmission in ER
/ 0.27/ ;
```

```
*         ------------
*          TABLES
*         ------------

Table faref2w(fn,wn) gives fare per kg from coalfield to washery
nodes
     WW1   WW2
RNJ  100   400
JHA  300   300
SNG  400   300  ;

Table faref2p(fn,pn) gives fare per kg from mine to plant nodes
     BDRP   INDP    TITG
RNJ  5000   4000    5000
JHA  3000   3000    8000
SNG  4000   3000    6000 ;


Table farew2p(wn,pn) gives fare per kg from washery to plant nodes
     BDRP  INDP  TITG
WW1  200   700    200
WW2  100   500    600 ;

Table dist(pn,pn) gives the distance between power plant nodes
      BDRP     INDP   TITG
BDRP    0       50    1300
INDP   50       0     1350
TITG  1300    1350     0


*        -------------
*         VARIABLES
*        -------------
Variables

qtymined(fn,gcol) gradewise extraction from each coalfield in mt

qtyf2w(fn,wn,gcol) gradewise quantity shipped from coalfield to
washery in mt

qtyf2p(fn,pn,tch,g) gradewise quantity shipped from coalfield to
plant in mt

calvalwsh(wn,gcol) calorific value of coal output from washery in
kcal per kg

capwsh(wn) capacity of washery plant in Mt per year

qtyw2p(wn,gcol,pn,tch) gradewise quantity shipped from washery to
plant

qtyinwsh(wn,gcol) gradewise quantity input to washery in Mt

qtyoutwsh(wn,gcol) quantity output from washery of grade DG in Mt

qtyashwsh(wn) quantity of ash produced from washery in Mt

plfpow(pn,tch) PLF of plant indicating utilization
```

```
cappow(pn,tch) capacity of plant in MW

qtyatpow(pn,tch,g) gradewise quantity of coal at plant in mt

uheatatp(pn,tch) useful energy required at plant in Mcal

qtybashpow(pn) quantity of bottom ash produced of coal in mt

qtyfashpow(pn) quantity of fly ash produced from coal in mt

powgen(pn,tch) output from each plant in Mwh

transNR(NR,NR) transmission between nodes in the Northern region

transER(ER,ER) transmission between nodes in the Eastern Region

spm(pn) spm emissions in mt at each pn

totspm total spm in tonnes

sox(pn) sox emissions in mt at each pn

totsox total sox all India in tonnes

nox(pn) nox emissions in mt at each pn

totnox total nox in tonnes

z total system cost ;

Free variable z ;
Positive variables
qtymined,qtyf2w,qtyf2p,calvalwsh,capwsh,qtyw2p,qtyinwsh,qtyoutwsh,qty
ashwsh,
transNR,transER,cappow,qtyatpow,uheatatp,qtybashpow,qtyfashpow,plfpow
,powgen;

*     -------------
*      EQUATIONS
*     -------------

Equations
mxsupcol(fn,gcol) fieldwise gradewise max supply constraint of coal

minebal(fn,gcol) production balance equal qty shipped to plant and
washery

mxwshcol(wn) input gradewise max constraint of coal per washery

* coalqty(pn,tch,g,fn,gcol) gradewise coal qty picked at plant

wshcolbal(wn,gcol) washery coal balance qty washed equals qty shippec
to plants

wshcolbal2(wn,gcol) washery coal balance qty at washery equals sum o:
qty from fields

wshiobal(wn,gcol) washery input output balance equation

wshashbal(wn) washery ash based on ash percent and coal qty washed
```

```
capoldwsh(wn) lower bound for washery capacity in case of existing
plant

mxpow(pn,tch) maximum power generation constarint in each power unit

* colpowbalD(pn,tch) coal consumption at plant equals qty shipped f2p
and w2p

colpowbalE(pn,tch) coal consumption at plant equals qty shipped f2p
and w2p

colpowbalF(pn,tch) coal consumption at plant equals qty shipped f2p
and w2p

colpowbalG(pn,tch) coal consumption at plant equals qty shipped f2p
and w2p

uheat(pn,tch) useful heat required at each plant in Mcal

coalneed(pn,tch) power generation balance at each power unit

powbalNR demand in NR not more than self generated and net
transmitted power

powbalER demand in ER not more than self generated and net
transmitted power

cappower(pn,tch) plant capacity constraint for existing units

cappowold(pn,tch) plant capacity constraint for old units

uppercap(pn,tch) upper bound on capacity of unit in MW

powashbal(pn) ash at plant equals product sum of ash rate and coal
burnt

spmemit(pn) SPM balance equation

spmtotal total SPM emitted

noxemit(pn) NOX balance equation

noxtotal total NOX emitted

soxemit(pn) SOX balance equation

soxtotal total SOX emitted

* calbal(wn,gcol) calorific value balance relationship

costsys system cost to be minimized;

* --------------------------------------------------------
*  Constraints are as follows:
* --------------------------------------------------------

* --------------------------------------------------------
* gradewise capacity of the field is set as parameter
* and qty mined from that field should be less than this
* --------------------------------------------------------
mxsupcol(fn,gcol).. capfld(fn,gcol) =g= qtymined (fn,gcol);
```

```
* ---------------------------------------------------------
* the quantity that is mined must either go to the washeries
* or to the plants
* ---------------------------------------------------------
minebal(fn,gcol).. qtymined(fn,gcol) =e=
sum((pn,tch),qtyf2p(fn,pn,tch,gcol))+
sum((wn),qtyf2w(fn,wn,gcol));

* ---------------------------------------------------------
* this is the balance equation between input and output of
* coal in the washery - output is all same grade
* ---------------------------------------------------------

wshiobal(wn,gcol).. sum((pn,tch),qtyw2p(wn,gcol,pn,tch)) =e=
sum(fn,(((100-ashper(fn,gcol)-
moistper(fn,gcol))/100)*qtyf2w(fn,wn,gcol)));

* ---------------------------------------------------------
* this equation sets the maximum capacity of washery which
* is set by the input capacity
* ---------------------------------------------------------
mxwshcol(wn).. capwsh(wn) =g= sum(gcol,qtyinwsh(wn,gcol));


* ---------------------------------------------------------
* this equation translates the power generation at a unit to
* the reqirement of coal of certain grade in tonnes
* ---------------------------------------------------------

* coalqty(pn,tch,g,fn,gcol).. qtyatpow(pn,tch,g) =e=
(powgen(pn,tch)*850000/calval(fn,gcol));

* ---------------------------------------------------------
* this is the balance for coal output from washery to the
* various plants
* ---------------------------------------------------------
wshcolbal(wn,gcol).. qtyoutwsh(wn,gcol) =e=
sum((pn,tch),qtyw2p(wn,gcol,pn,tch));

* ---------------------------------------------------------
* NEW: this is the balance for coal at washery and that shipped to it
* from various coalfields
* ---------------------------------------------------------
wshcolbal2(wn,gcol).. qtyinwsh(wn,gcol) =e=
sum((fn),qtyf2w(fn,wn,gcol));



* ---------------------------------------------------------
* this equation equates the ash at the washery with the input
* of coal in washery and ash production rate of washery
* ---------------------------------------------------------
wshashbal(wn).. qtyashwsh(wn) =e= (sum((fn,gcol),-
0.1308*(qtyinwsh(wn,gcol)*ashper(fn,gcol)))+32.231);

* ---------------------------------------------------------
* this is for the existing washery plants
* ---------------------------------------------------------
capoldwsh(wn).. capwsh(wn) =g= capwshlo(wn);
```

```
* -------------------------------------------------------
* NEW : calorific value of coal changes when it goes to the washery
* -------------------------------------------------------

* calbal(wn,gcol).. calvalwsh(wn,gcol) =e= -
0.0003*calval(fn,gcol)+1.2708;


* -------------------------------------------------------
*       capacity constraint of each power unit: the      *
*       maximum power generation from a unit in Gwh      *
*       is limited by the upper bound on plant capacity  *
*       and the PLF of the unit (which is fixed in this  *
*       case.                                            *
* -------------------------------------------------------
mxpow(pn,tch).. cappowup(pn,tch)*plfpowup(pn,tch)*8760 =g=
powgen(pn,tch);

* -------------------------------------------------------
* coal utilization balance at each power unit (To be checked)
* -------------------------------------------------------
*colpowbalD(pn,tch)..
*qtyatpow(pn,tch,'D') =e=
sum((fn),qtyf2p(fn,pn,tch,'D'))+sum((wn),qtyw2p(wn,pn,tch,'D'));
colpowbalE(pn,tch)..
qtyatpow(pn,tch,'E') =e= sum((fn),qtyf2p(fn,pn,tch,'E'));
colpowbalF(pn,tch)..
qtyatpow(pn,tch,'F') =e= sum((fn),qtyf2p(fn,pn,tch,'F'));
colpowbalG(pn,tch)..
qtyatpow(pn,tch,'G') =e= sum((fn),qtyf2p(fn,pn,tch,'G'));

* -------------------------------------------------------
* useful heat requirement at each plant in Mcal
* -------------------------------------------------------

uheat(pn,tch).. uheatatp(pn,tch) =e= powgen(pn,tch)*heatrate(pn,tch);


* -------------------------------------------------------
* equate useful energy rqd at plant(Mcal)with coal need(Mt)
* -------------------------------------------------------
* coalneed(pn,tch).. uheatatp(pn,tch) =l= (( sum((fn,gcol),
qtyf2p(fn,pn,tch,gcol)*calval(fn,gcol)) +
sum((wn,gcol),qtyw2p(wn,gcol,pn,tch)*calvalwsh(wn,gcol)) ))*10**6;

coalneed(pn,tch).. uheatatp(pn,tch) =l= (( sum((fn,gcol),
qtyf2p(fn,pn,tch,gcol)*calval(fn,gcol)) +
sum((fn,wn,gcol),qtyw2p(wn,gcol,pn,tch)*(-
0.0003*calval(fn,gcol)+1.2708)) ))*10**6;

* -------------------------------------------------------
* power I-O balance at each power unit in each region
* -------------------------------------------------------
powbalNR.. demandN =l=
sum((NR,tch),powgen(NR,tch))+sum((NR,NR1),transNR(NR1,NR)*(1-
lossfac*dist(NR1,NR))) - sum((NR,NR1),transNR(NR,NR1));

powbalER.. demandE =l= sum((ER,tch),powgen(ER,tch))+
sum((ER,ER1),transER(ER1,ER)*(1-lossfac*dist(ER1,ER))) -
sum((ER,ER1),transER(ER,ER1));
```

```
* ---------------------------------------------------------
* power output
* ---------------------------------------------------------

cappower(pn,tch).. powgen(pn,tch) =e=
cappow(pn,tch)*plfpowup(pn,tch)*8760;

* ---------------------------------------------------------
* capacity of existing power plant is given as lower bound
* ---------------------------------------------------------
cappowold(pn,tch).. cappow(pn,tch) =g= cappowlo(pn,tch);


* ---------------------------------------------------------
* upper bound on capacity of existing unit is set
* ---------------------------------------------------------

uppercap(pn,tch).. cappow(pn,tch) =l= cappowup(pn,tch);


* ---------------------------------------------------------
* fly-ash balance at power plants
* ---------------------------------------------------------
powashbal(pn).. qtyfashpow(pn) =e=
sum((tch,g),qtyatpow(pn,tch,g)*powprfash(g));

* ---------------------------------------------------------
* Calculate various emission
* ---------------------------------------------------------
spmemit(pn).. spm(pn) =e=
sum((tch,g),(spmfac(tch,g)*qtyatpow(pn,tch,g)));

spmtotal.. totspm =e= sum((pn),spm(pn));

noxemit(pn)..nox(pn) =e=
sum((tch,g),(noxfac(tch,g)*qtyatpow(pn,tch,g)));

noxtotal.. totnox =e= sum((pn),nox(pn));

soxemit(pn)..sox(pn) =e=
sum((tch,g),(soxfac(tch,g)*qtyatpow(pn,tch,g)));

soxtotal.. totsox =e= sum((pn),sox(pn));

* ---------------------------------------------------------
* objective function
* ---------------------------------------------------------
costsys.. z =e= sum((fn,wn,gcol),qtyf2w(fn,wn,gcol)*faref2w(fn,wn))+

sum((fn,pn,tch,gcol),qtyf2p(fn,pn,tch,gcol)*faref2p(fn,pn))+

sum((wn,gcol,pn,tch),qtyw2p(wn,gcol,pn,tch)*farew2p(wn,pn))+
                sum((fn,gcol),extrcost(fn,gcol)*qtymined(fn,gcol))+
                sum((wn),capwsh(wn)*wshcostinv(wn))+
                sum((pn,tch),cappow(pn,tch)*powcostinv(pn,tch))+
                sum((pn,tch),powgen(pn,tch)*powcostopm(pn,tch))+
                sum((wn,gcol),qtyoutwsh(wn,gcol)*wshcostopm(wn))-
                sum((pn),qtyfashpow(pn)*powutlash(pn)*savbrik)-
                sum((wn),qtyashwsh(wn)*wshutlash(wn)*savbrik);

        -------------------------------------------------
```

```
* for execution
* -----------------------------------------------------------
Model Coal /all/;
option iterlim = 2000;
options solprint=off;
solve Coal using lp minimizing z;
display cappow.l, powgen.l, qtyatpow.l, qtyf2p.l, qtyf2w.l, qtyw2p.l,
qtymined.l, heatrate;
```

Section 6 Scenario Possibilities

In the first phase the model has been set for the year 1996/97. During the second phase, the possible scenarios that may be attempted include the following:

- Most likely scenario (baseline) for future year (2006/07)
- Optimal (unconstrained) scenario
- Clean coal (increased coal washing) scenario
- Scenario with reduced coal share (fuel substitution) in power generation
- Scenario for increased efficiency at plant end

Based on further discussions with the experts in the field, the setting up of meaningful alternative scenarios would be done in Phase II of the project.

Section 7

7.1 Future Work

For the year 1999-2000, it is proposed that the COLINK model developed in the 1st phase of the project would be further refined and used for a quantitative scenario analysis from the perspective of various economic, technical and environmental standpoints in light of the changing policies in the coal and power sectors. This would be highly relevant at this juncture since the supply of indigenous coal to power plants is facing threats both by other fuels as well as imported coal. Whether it is the inefficiencies and organizational failure in the coal and transportation sectors or the economies in use of other fuels needs to be understood. The second phase of the study therefore would attempt to address this critical question with a view to suggest suitable measures and policy recommendations relevant to the sector.

The 2nd phase of the project would involve inputs from experts in the coal and power sectors as well as from policy makers. Also, the exchange programme between TERI and the University of Kyoto is expected to be continued during the year to facilitate further development of the model and scenario analysis. The second phase of the project would terminate with the submission of a comprehensive report about the results of the work done during the 2 years.

7.2 Limitations

The availability of reasonably accurate and detailed data is extremely important for generating rational scenarios from the model. The data for the base year (1996/97) has been compiled to some extent in Phase - I of the project. However, projections for the future time period and more detailed data input will be required ~~in the second~~ phase.

Power generation
Coal supply linkage
Coal based power
Coal utilization
Literature review